Guidelines for regional liquefaction hazard mapping

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Annual Project Summary
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Investigations Undertaken:

This project is a one-year study to develop guidelines for incorporating geotechnical data in regional liquefaction hazard mapping projects. Regional liquefaction hazard mapping projects have been completed for many (>20 NEHRP funded) projects around the United States and each project has used a slightly different methodology. Many of the first projects relied solely on surficial geology to assess liquefaction hazard. The current trend is to include geotechnical boring data along with the surficial geology when characterizing the liquefaction susceptibility. One of the challenges in completing these projects is deciding how to combine surficial geology information, which is on a regional scale and geotechnical boring information, which is on a site-specific scale.

The project will reevaluate completed regional liquefaction hazard mapping projects to develop guidelines and criteria for collecting geotechnical borehole data to quantify liquefaction susceptibility across a geologic unit. The proposed criteria will expressly include characterization of inherent geologic variability. Statistical, probabilistic, and geostatistical analyses will be used to characterize sample distributions by geologic unit in order to assess overall variability. In addition, we will assess the impact of sparse sampling on liquefaction susceptibility characterization. More accurate, detailed maps of liquefaction susceptibility that account for inherent geologic variability will considerably improve the assessment of liquefaction hazards and allow communities to better plan and mitigate the effects of liquefaction on the built environment.

We are evaluating differences in liquefaction characterizations based on standard penetration tests (SPT), cone penetration tests (CPT), and shear wave velocity (Vs). We are also assessing the variability within and between geologic units.

Data:

We have identified several liquefaction hazard mapping projects with subsurface datasets as listed in Table 1. To start the work, we have focused on liquefaction hazard mapping projects in the San Francisco Bay. Our preliminary results focus on the East Bay mapping effort (Holzer et al. 2002). The remainder of the projects will be evaluated in the next stages of our work.

Table 1. Identified liquefaction hazard mapping projects

Project Name	Location	Principal Investigator	Funding	Funding Number	Data Types (# of points)		
					SPT	CPT	VS
Liquefaction Hazard and Shaking Amplification Maps	East Bay, San Francisco Bay Area	Holzer et al.	USGS		100+	210 scpt	
Central US Shear Wave Velocity Database with Accompanying Geologic/Geotechnical Information	Indiana, Kentucky and Illinois	Robert A. Bauer	USGS ERG	04-HQ-GR-0074		30	60
Liquefaction Susceptibility Mapping	St. Louis, Missouri and Illinois	Justin T Pearce and John N. Baldwin	USGS ERG	03-HQ-GR-0029	200+		10
Liquefaction Hazard Mapping	Boston	Brankman & Baise	USGS ERG	02-HQ-GR-0040 & 0036	2963		
Liquefaction Susceptibility Mapping	Memphis/Shelby County, TN	Glenn Rix	USGS ERG	01-HQ-AG-0019	200+	29+	
Liquefaction-susceptibility and seismic soil-type maps of Geophysical Surveys	Anchorage, Alaska	Rodney Combellick	USGS ERG	01-HQ-GR-0006	900+		
Characterization of subsurface sediments	Southern San Francisco Bay	Hitchcock and Helley	USGS ERG	99-HQ-GR-0097	1600		
Liquefaction Susceptibility Mapping for Selected Urban Areas	Central Puget Sound, WA	Stephen Palmer	USGS ERG	99-HQ-GR-0074	504		
Liquefaction Susceptibility of the Hollister Area	San Benito County, CA	Lewis Rosenberg	USGS ERG	1434-HQ-97-GR-03125	300		
Relative Liquefaction and Amplification of Ground Motion Hazard Maps	Greater Victoria, BC	Patrick Monahan	BC Ministry of Energy and Mines	Geoscience Map 2000-3	5000		

East Bay, San Francisco Bay, California
The CPT data used were obtained from a USGS Open-File Report completed by Holzer et al. (2002) for the Oakland, California area. The USGS characterized this region with a dense set of 210 CPTs after the 1989 Loma Prieta Earthquake. Additionally, the surficial geology of the area was mapped by the USGS (Knudsen et al, 2000) and includes mapped areas of the surficial effects due to liquefaction (sand boils, lateral spreading, etc.) from the Loma Prieta Earthquake.

We obtained the SPT data from the California Geological Survey – Seismic Hazards Mapping Program (http://gmw.consrv.ca.gov/shmp/). The California Geological Survey compiled borehole information from both private and public projects across the state and made it available to the public. For this study, we evaluated only the samples which were completed using the procedures described in ASTM D1586-99. Both the CPT and SPT data are shown on a map of the area in Figure 1. The surficial geology is also shown along with mapped areas of surficial effects due to liquefaction from the Loma Prieta earthquake.

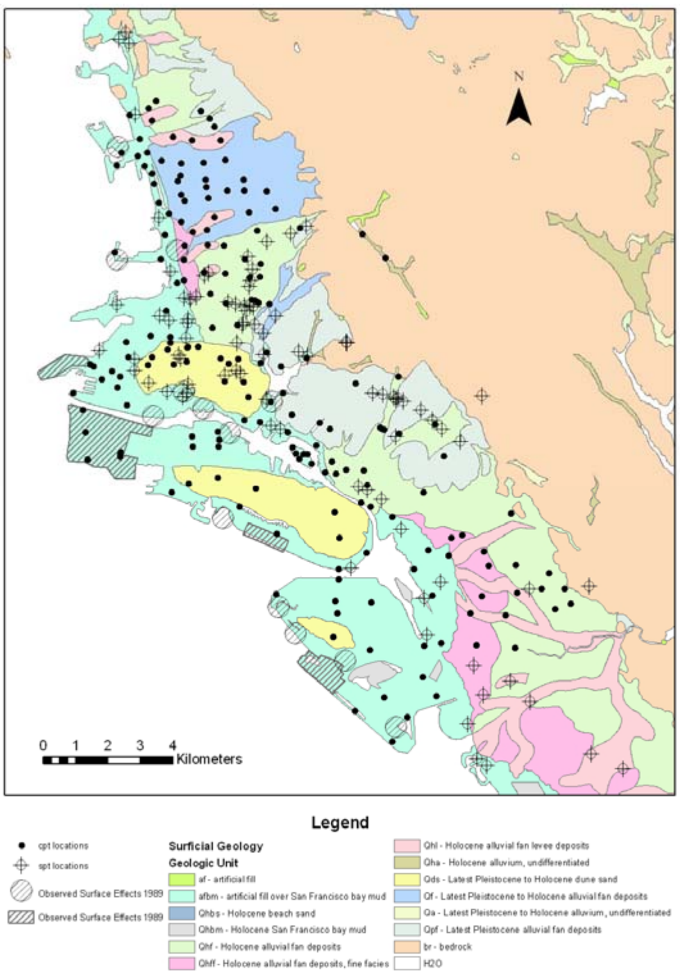

Figure 1. Map of East Bay Liquefaction Mapping Project

Methodology:

The various datasets have subsurface data in the form of cone penetration tests (CPT), standard penetration tests (SPT) and shear wave velocity (Vs). To date, we have focused on CPT and SPT data and outline our procedure for evaluating liquefaction potential as described below. We are using the liquefaction potential index (LPI) developed by Iwasaki et al. (1982). We have also looked into using probability-based liquefaction methods and may incorporate them in further stages of this work.

For the CPT, we calculated the cyclic stress ratio (CSR) for each profile using the equation proposed by Seed and Idriss (1971):

$$CSR = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d$$

where a_{max} is the peak horizontal acceleration, g is the acceleration of gravity, σ_{vo} and σ'_{vo} are the total and effective overburden stresses and r_d is the stress reduction coefficient . To estimate the peak horizontal acceleration, we chose a station within the area of study which had recorded ground motions during the 1989 Loma Prieta earthquake from the Cosmos Virtual Data Center (COSMOS - http://www.cosmos-eq.org/). The station we chose is located in Oakland, CA on the Outer Harbor Wharf, and it recorded a peak ground acceleration of approximately 280 cm/s^2 during Loma Prieta. We used the stress reduction coefficient, r_d, recommended by Youd et al. (2001).

To determine the soil types that are considered non-liquefiable along the CPT profile, we estimated the grain characteristics, I_c, and the normalized tip resistance, q_{c1N}, directly from the CPT data as described Robertson and Wride (1998). Using a correction factor based on the I_c and the q_{c1N}, we calculated an equivalent clean sand normalized CPT tip resistance, $(q_{c1N})_{cs}$, (Robertson and Wride, 1998). We assumed for this study that if the soils had an $I_c > 2.6$, then they are likely to be too clay or silt-rich to liquefy. However, it is recommended by Youd et al. (2001) that soils with an $I_c > 2.4$ should be sampled and tested to confirm the soil type and the liquefiability. We determined the cyclic resistance ratio (CRR) along the CPT profile using the clean sand normalized tip resistance as recommended by Robertson and Wride (1998).

For the SPT, we calculated the CSR for each reported blow count using the same equations and assumptions as discussed for the CPT. We corrected the blow counts using the recommendations from Youd et al. (2001) along with the overburden stress correction factor from Kayen et al. (1992). In order to correct for the affect of fine grained soils, we used the fines content to determine the equivalent clean sand corrected blow count (Youd et al. 2001). The fines content used for each sample was either reported in the borehole data as the percent fines passing the #200 sieve or estimated based on the lithology. We then approximated the CRR using the clean-sand normalized blow counts as recommended in Youd et al. (2001).

LPI

The liquefaction potential index (LPI) is a measure of the effects of liquefaction based on the severity of liquefaction and the depth and width of the liquefiable zones. The LPI is evaluated for the top 20 meters of a soil profile. The CPT and SPT profiles that are shorter than 10 meters were not evaluated. This gave us 194 CPT sites and 88 SPT sites within our area of study. We determined that there was little significant increase in LPI for the CPT and SPT profiles between 10 – 20 meters. Less than 10% of the CPT and only 1% of the SPT showed a significant increase (>2) in the LPI between this range. Typically, the sites that have significant increases between 10 – 20 meters have a high liquefaction potential for the top 10 meters as well.

The factor of safety against liquefaction is given as:

$$FS = \left(\frac{CRR_{7.5}}{CSR} \right) MSF$$

where CSR is the calculated cyclic stress ratio generated by the design earthquake (e.g. Loma Preita), $CRR_{7.5}$ is the cyclic resistance ratio for magnitude 7.5 earthquake and MSF is the magnitude scaling factor. For this study, we used the revised MSF from Youd et al. (2001).

The LPI, based on the method by Iwasaki et al. (1982), is defined as:

$$LPI = \int_0^{20} F_L \cdot w(z) \cdot dz$$

where w(z) = 10 – 0.5z (z=depth in meters) and dz is the differential increment of depth. We used the liquefaction potential categories proposed by Sonmez (2003) which defined F_L as:

$F_L = 0$ for $FS \geq 1.2$
$F_L = 1 - FS$ for $FS < 0.95$
$F_L = 2 \times 10^6 e^{-18.427FS}$ for $1.2 > FS > 0.95$

For the SPT, we used the lithology classifications for each borehole to remove layers which we would expect to be too clay or silt-rich to liquefy. We evaluated the non-liquefiable soil layers based on recommendations from Andrews and Martin (2000). If the recommendation stated that further testing was required, we continued the evaluation of the liquefaction potential of the sample. We interpolated between SPT locations to create a continuous profile.

For the CPT, we used a descritized form of the LPI given by Luna and Frost (1998):

$$LPI = \sum_{i=1}^{NL} w_i F_{Li} H_i$$

where w_i and F_{Li} are determined, as discussed previously for the SPT, for each layer, H_i is the thickness of the discritized layer and NL is the number of CPT points in a profile. H_i is determined by the sample frequency of the CPT, which is 0.05 meters for this study.

For both the CPT and the SPT, we used the liquefaction potential classifications proposed by Sonmez (2003):

Liquefaction Potential Index (LPI)	Liquefaction Potential
0	Non-liquefied
$0 < F_L \leq 2$	Low
$2 < F_L \leq 5$	Moderate
$5 < F_L \leq 15$	High
$F_L > 15$	Very High

Preliminary Results:

Figure 2 and 3 show the LPI calculated for CPT and SPT, respectively. In order to evaluate the variability of liquefaction potential across the region, we queried the results by mapped surficial geologic unit. Figure 4 and 5 show the LPI distributions by surficial geologic unit for CPT and SPT, respectively. These figures show that the distribution of liquefaction potential within each geologic unit has high variability and that there is significant overlap between the geologic units. Our next steps are to evaluate the spatial variability between distinct surficial geologic units of the same designation and within surficial geologic units.

Once the analysis is complete for this first region, we will carry out similar analysis for the remaining mapped regions. Our final report will develop guidelines for liquefaction hazard mapping that will include considerations for geologic environment as well as subsurface data type and quantity.

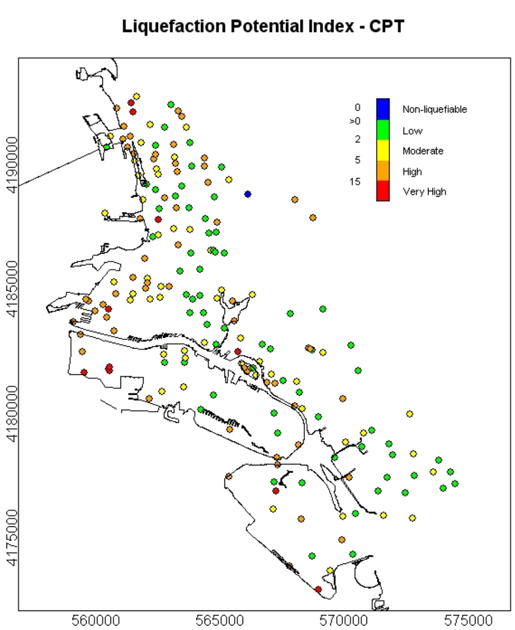

Figure 2. LPI for CPT

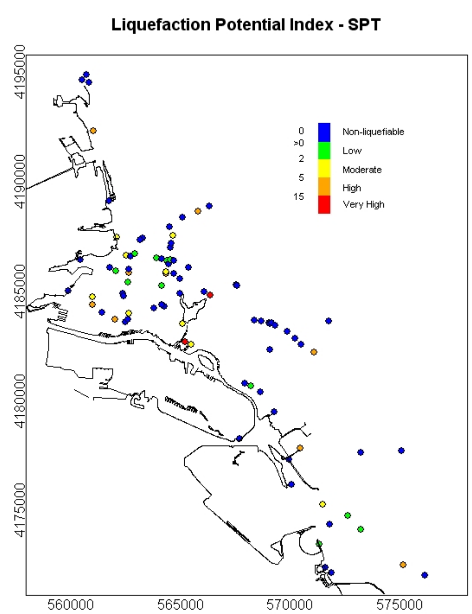

Figure 3. LPI for SPT

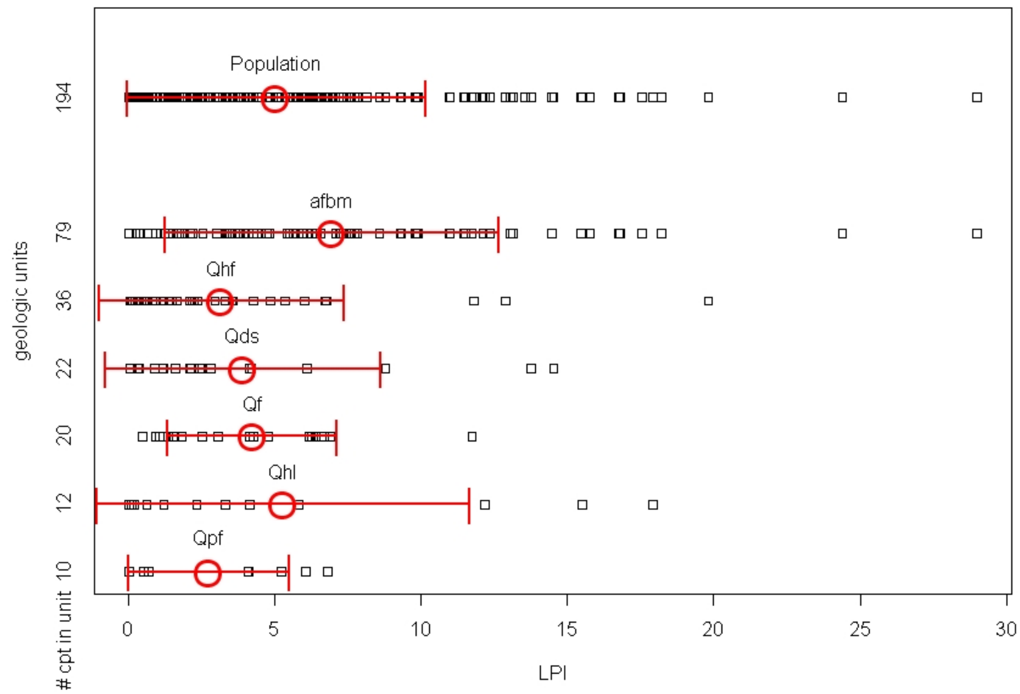

Figure 4. Distribution of LPI for CPT by mapped surficial geologic unit

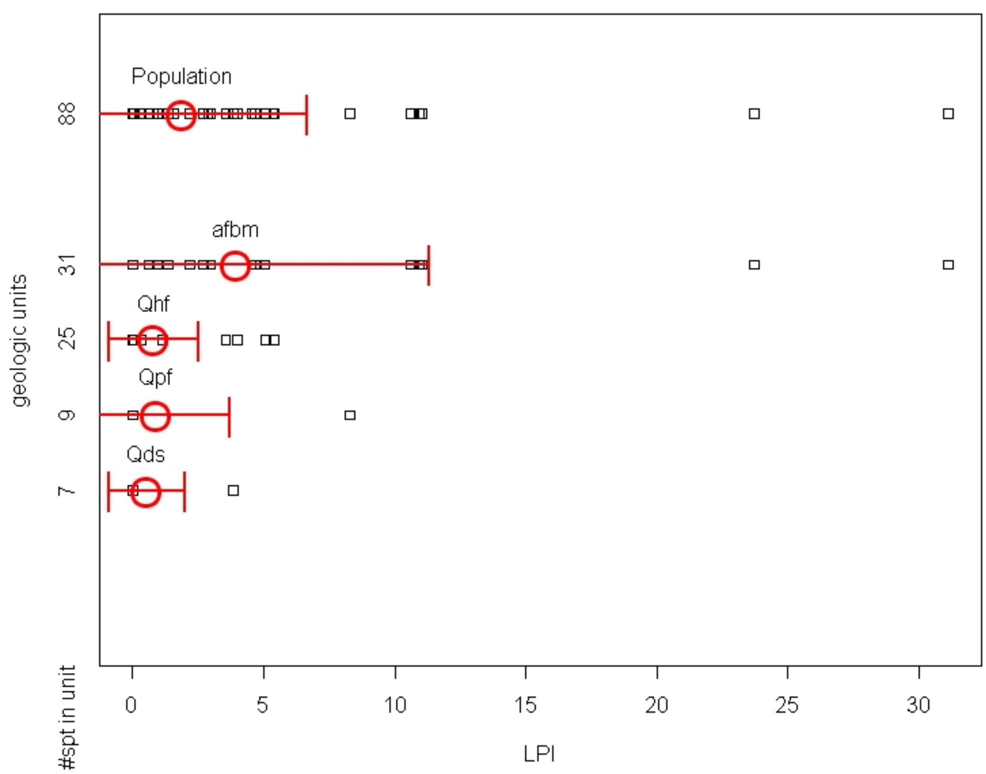

Figure 5. Distribution of LPI for SPT by mapped surficial geologic unit

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Program Element I: Products for Earthquake Loss Reduction
Keywords: Liquefaction, regional seismic hazard, surficial deposits, site effects

Non-technical summary:

This project is a one-year study to reevaluate completed regional liquefaction hazard mapping projects and develop guidelines for incorporating geotechnical data in regional liquefaction hazard mapping projects. Geotechnical data provide detailed information about the soil at a specific location. Regional liquefaction hazard mapping projects have been completed for many projects around the United States and each project has used a slightly different methodology. Many of the first projects relied solely on surficial geology to assess liquefaction hazard. The current trend is to include geotechnical data along with the surficial geology when characterizing the liquefaction susceptibility.

Reports Published:

None to date.